Large-Eddy-Simulations of Turbulent Thermonuclear Flames: The Key to Understand Stellar Explosions

Wolfgang Hillebrandt
MPI für Astrophysik
Garching

ScicomP13
RZG, July 16 - 20, 2007

In collaboration with ….

Friedrich Röpke (MPA),

Martin Reinecke (MPA),

Paolo Mazzali (MPA & Trieste),

Jens Niemeyer (U. Würzburg),

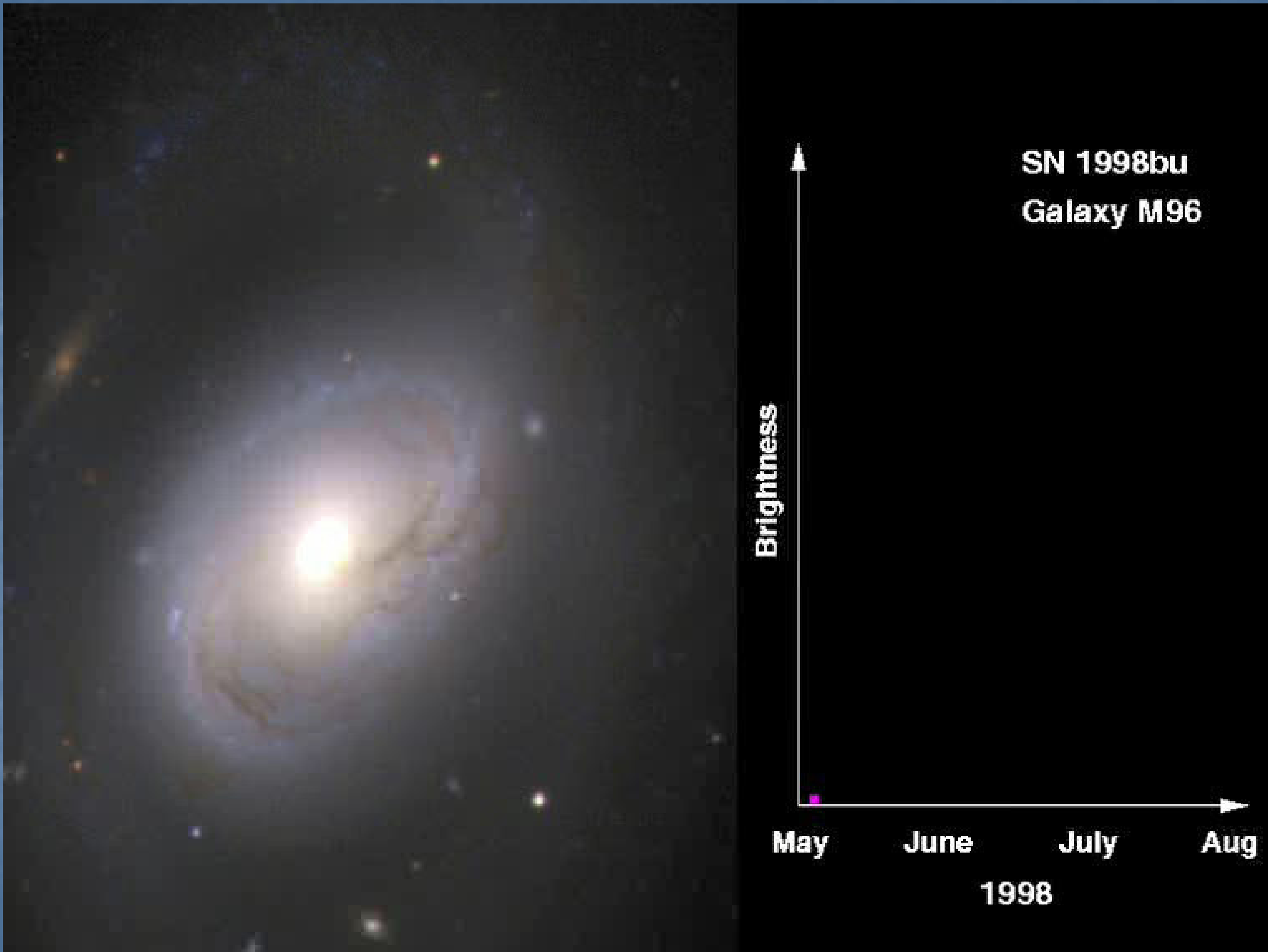
Wolfram Schmidt (U. Würzburg),

Sergei Blinnikov (ITEP Moscow),

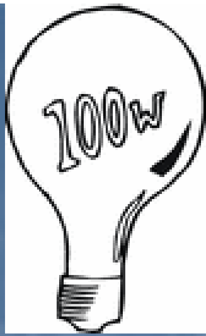
Elena Sorokina (ITEP Moscow),

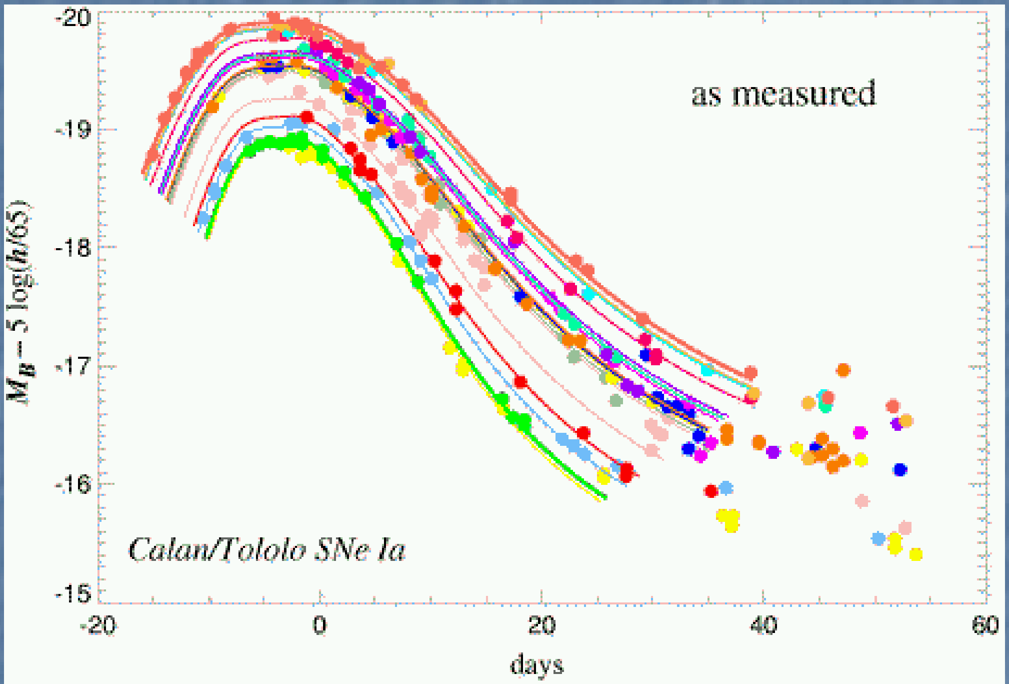
Stan Woosley (UC Santa Cruz),

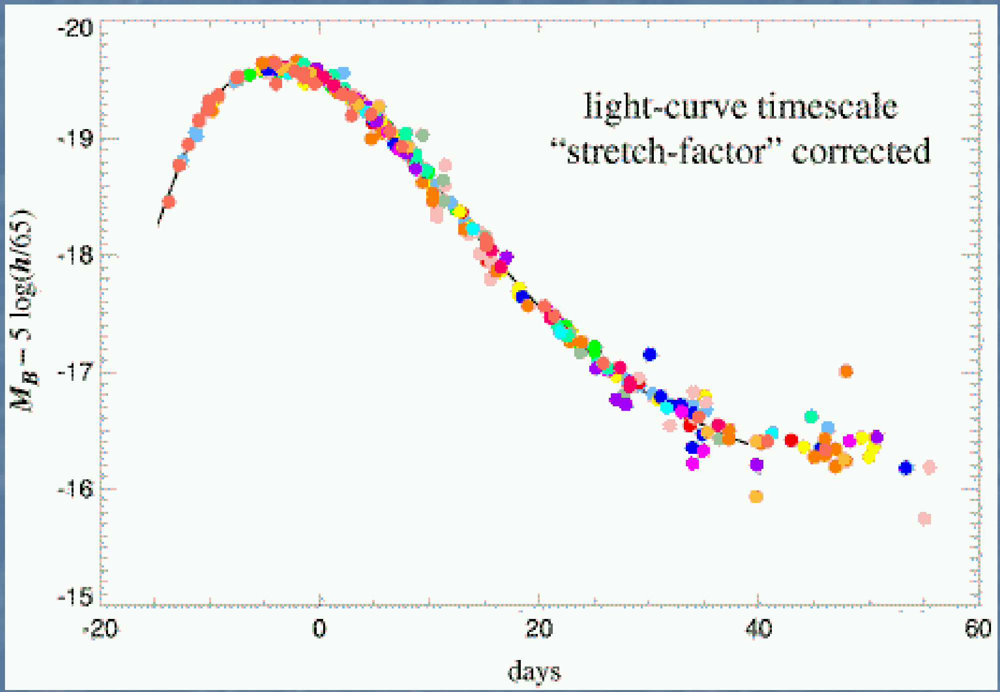
………………


SN 1998bu
Galaxy M96
Brightness
May
June
July
Aug
1998

“Supernova Cosmology”: The quest for precise luminosity distances!

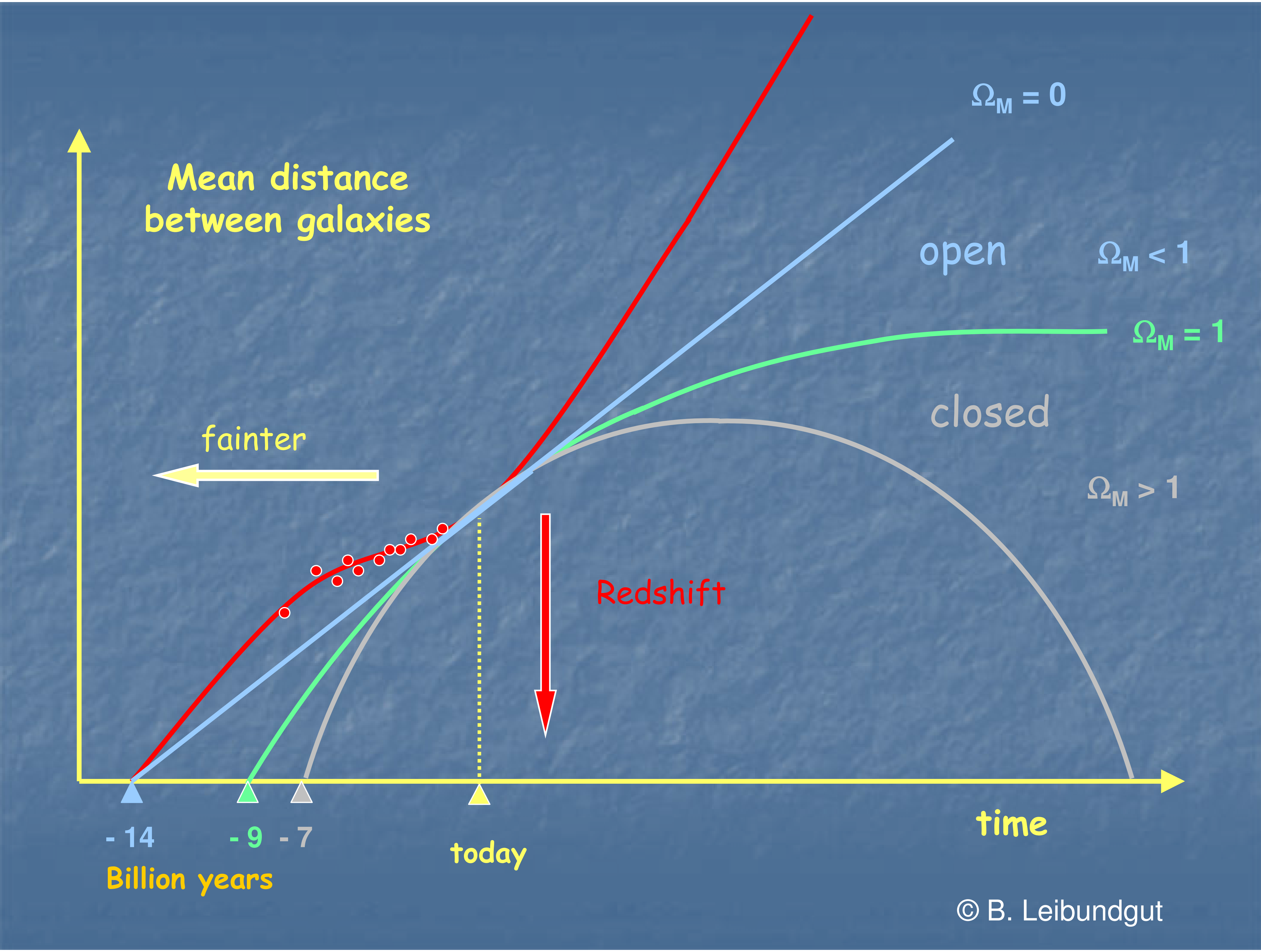






(B-band light curves; Calan/Tololo sample, Kim et al. 1997)

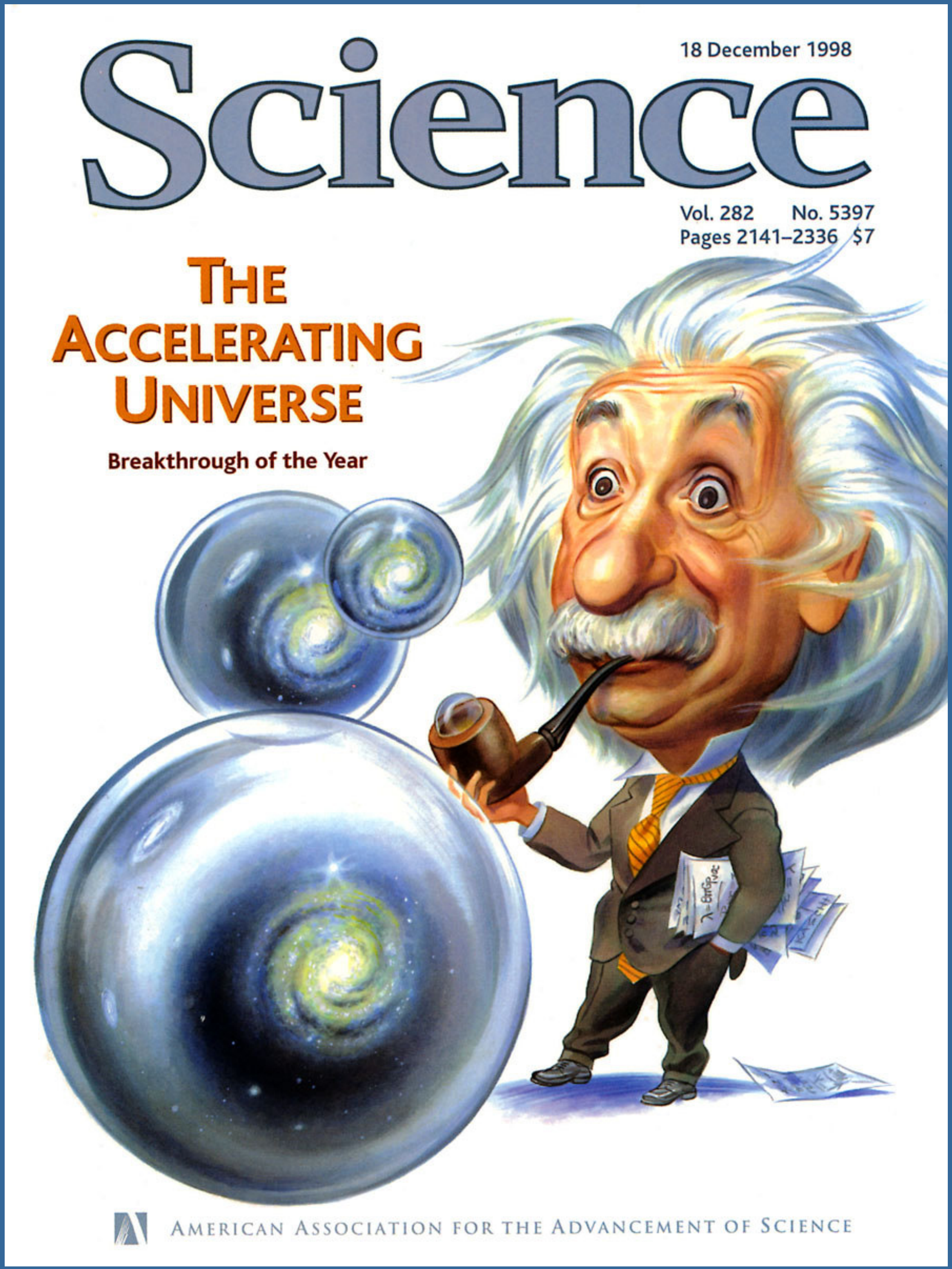
After calibration: SNe Ia look like good “standard candles”!



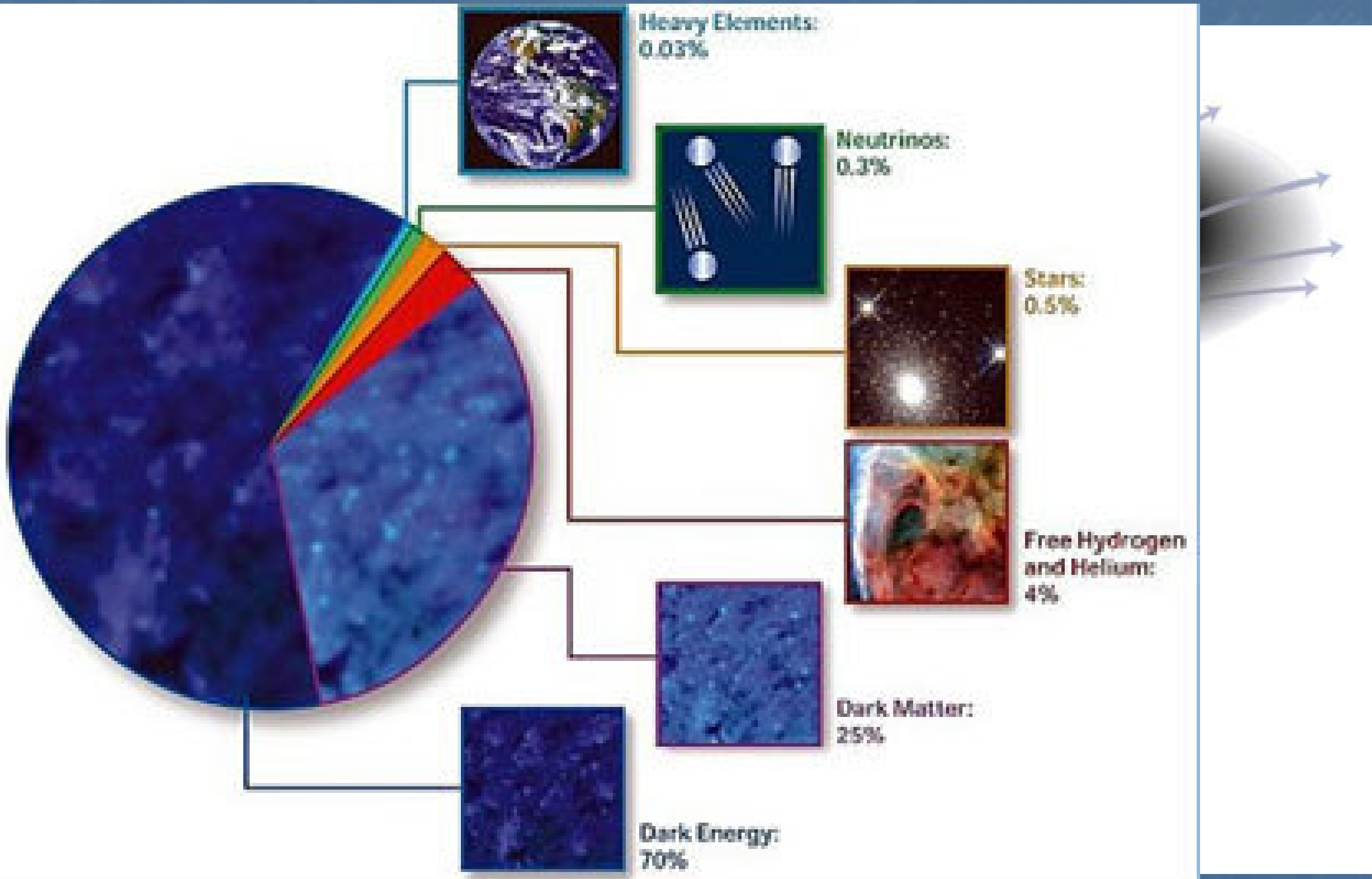
Mean distance
between galaxies
$\Omega_M = 0$
open
$\Omega_M < 1$
$\Omega_M = 1$
closed
$\Omega_M > 1$
fainter
Redshift
- 14
- 9
- 7
today
time
Billion years
© B. Leibundgut

Accelerating cosmic expansion ….

…. and the public response



The new cosmology ….



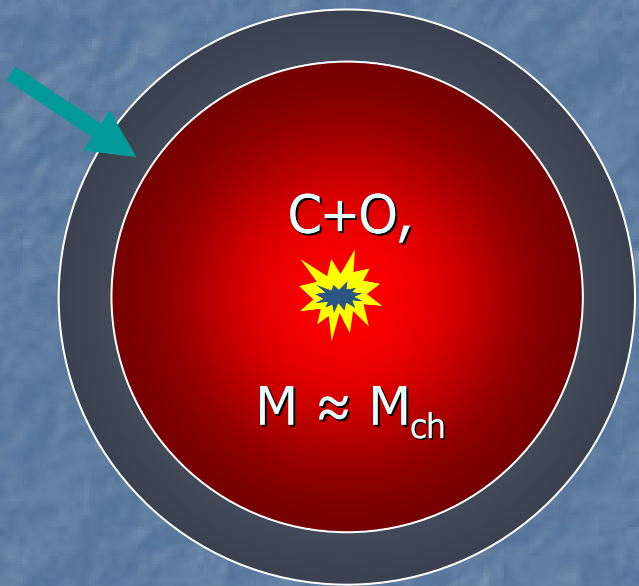
The “standard model” of a SN Ia

The "standard model" of a SN Ia

- White dwarf in a binary system
- Growing to the critical mass (M_{Chan}) by mass transfer

How does the model work?

He (+H)
from binary
companion



Density ~ 10^9 - 10^{10} g/cm^3

Temperature: a few 10^9 K

Radii: a few 1000 km

Explosion energy:

Fusion C+C, C+O, O+O → "Fe"

Laminar burning velocity:

$s_L \sim 100$ km/s $<< c_S$

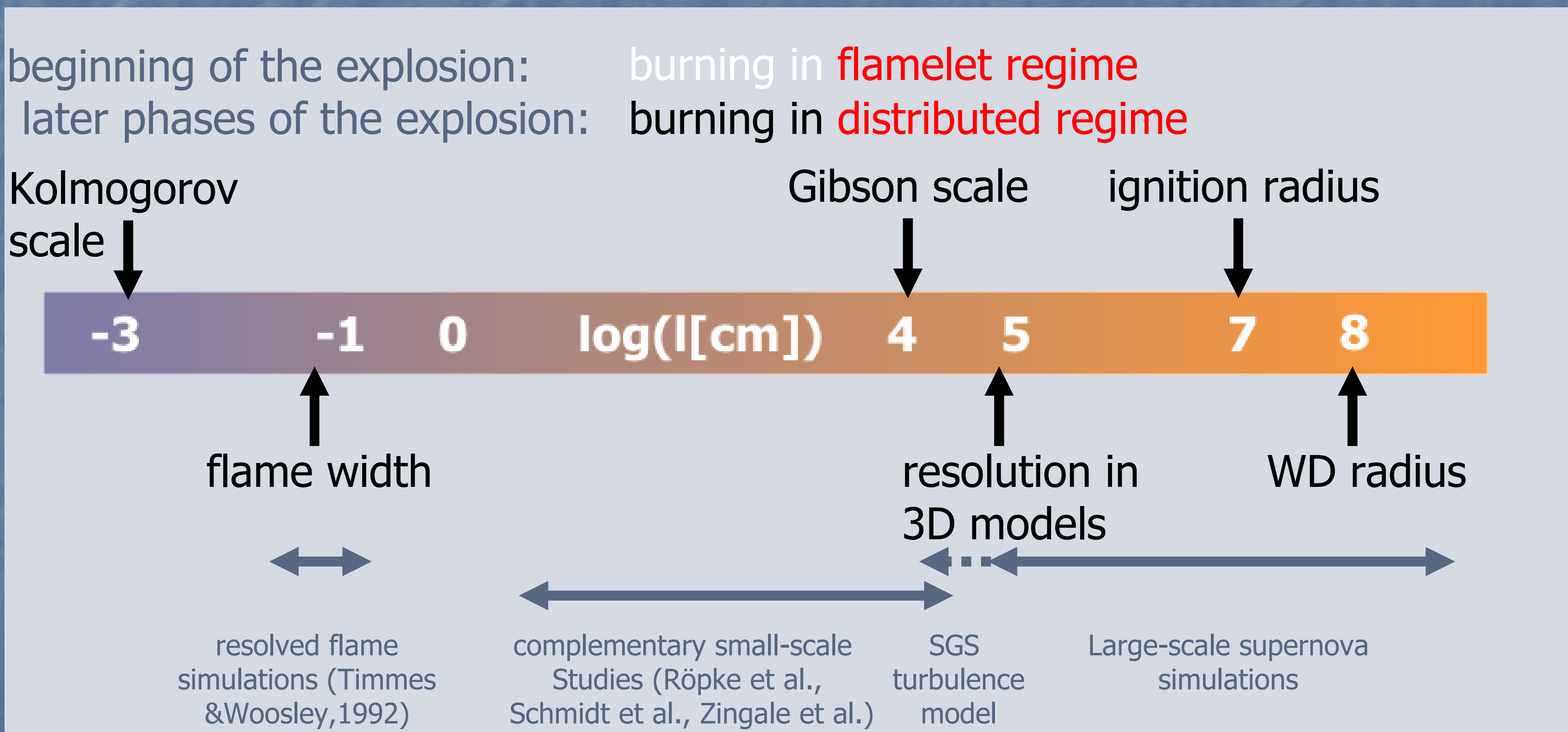
Too little is burned!

The physics of turbulent combustion

- In a star: Reynoldsnumber ~ 10^{14} !
- In the limit of strong turbulence: $U_B \sim s_T$!
- Everydays experience: *Turbulence increases the burning velocity.*
- Physics of thermonuclear burning is very similar to premixed chemical flames.

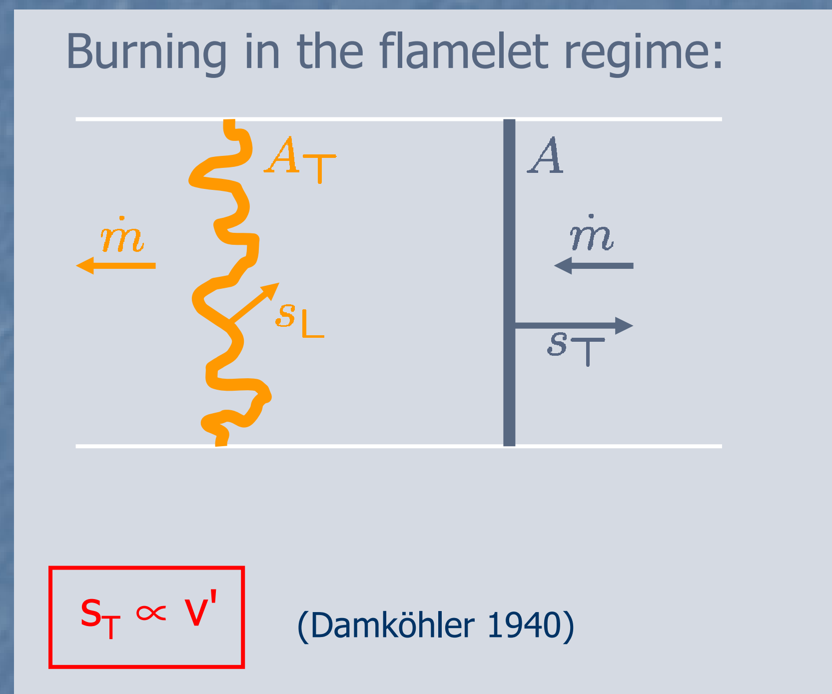
Relevant length scales in simulations of SN Ia explosions

(Gibson scale $s_L = v'$: below turbulence does not affect flame propagation)



Turbulent deflagration

- most parts of the SN Ia explosion: turbulence does not penetrate internal flame structure: flamelet regime of turbulent combustion



- in very late stages: turbulence may affect burning microphysics $\rightarrow$ onset of distributed burning regime

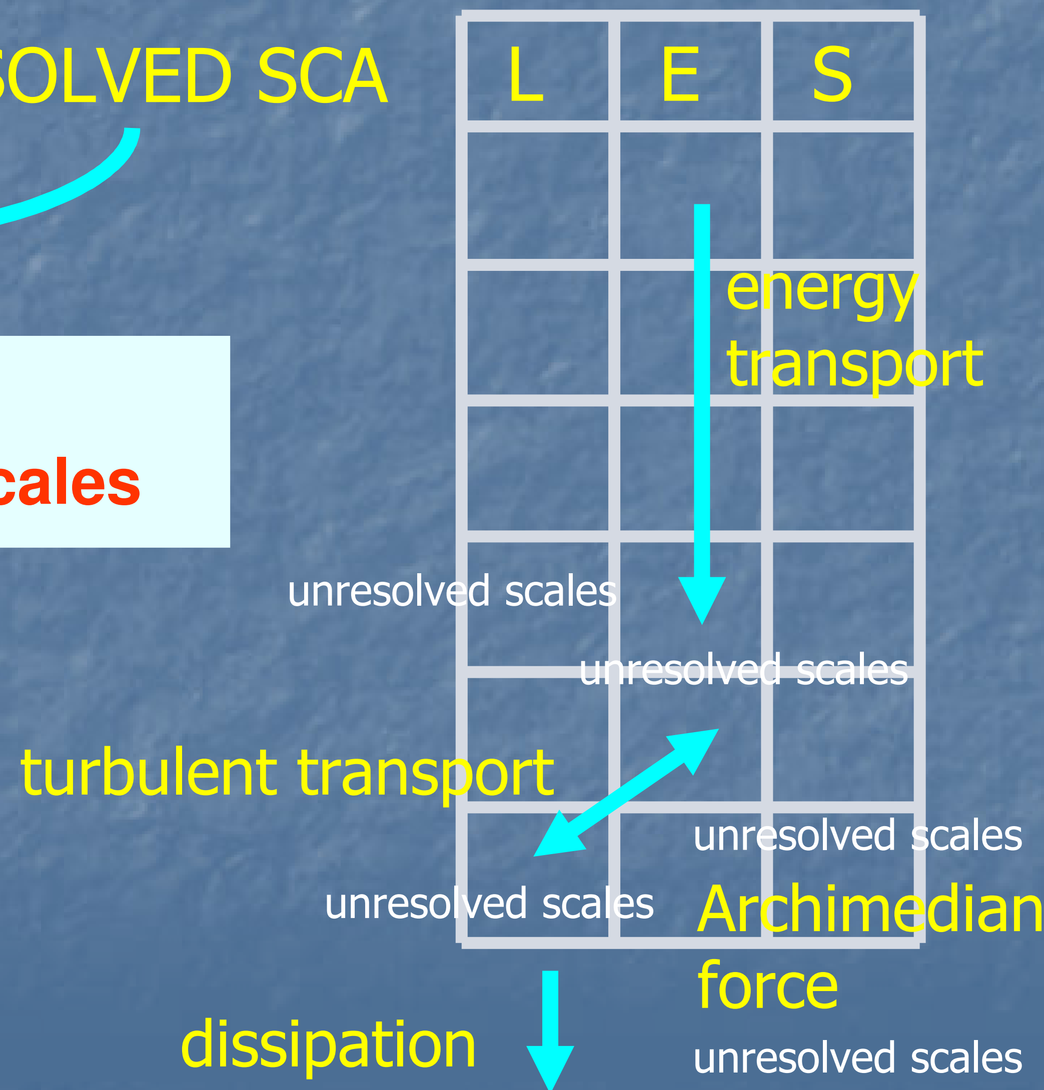
Numerical Implementation I

- Large Eddy Simulation (LES) approach
- Subgrid-scale turbulence model (Niemeyer et al., 1995; Schmidt et al., 2005)

RESOLVED SCA

Balance equation for turbulent kinetic energy on unresolved scales

Determines turbulent velocity fluctuations v' !



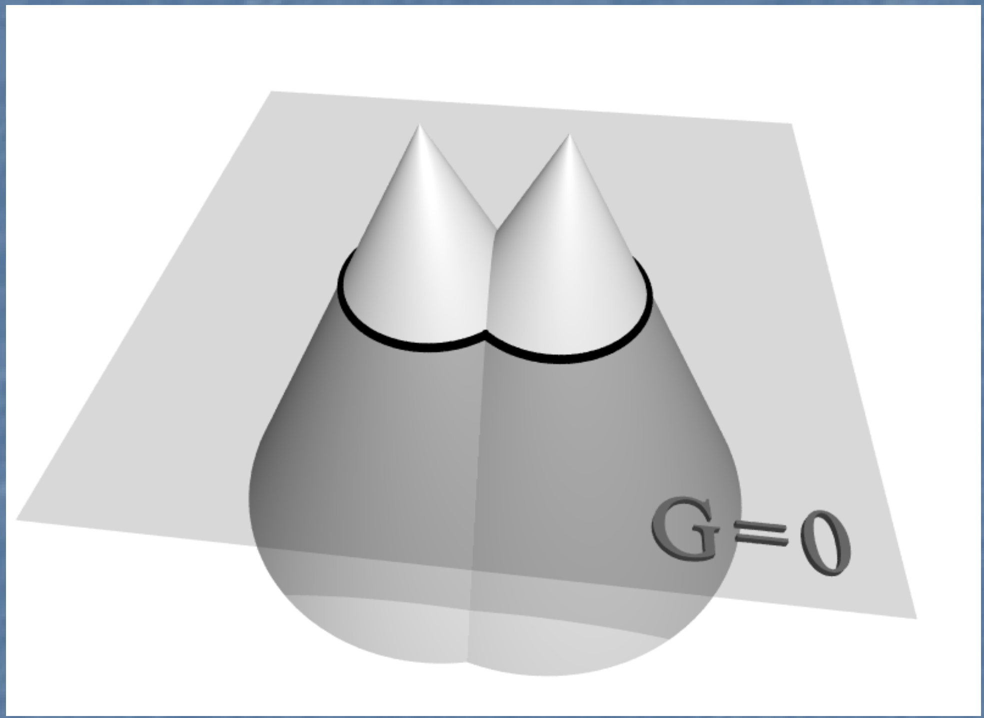
Numerical Implementation II

- seen from scales of WD: flame is discontinuity between fuel and ashes
- flame propagation via Level Set Method
- associate flame front with

$$\Gamma = \{\vec{r} \mid G(\vec{r},t) = 0\}$$

- distance function G,
  G<0 in fuel, G>0 in ashes
- equation of motion:

$$\frac{\partial G}{\partial t} = (\mathbf{v}_\mathrm{u}\mathbf{n} + s_\mathrm{T}) \mid \nabla G \mid$$



- simplified description of burning: everything behind G=0 isosurface is nuclear ash; depending on fuel density at burning: intermediate mass elements (“Mg”) or NSE (mixture of “Ni” and ^{4}He)

Ingredients to the present code in more detail *(the SUCCESs code)*

1. Subgrid-scale modeling

(from technical combustion; W. Schmidt et al. 2005, 2006)

$s_T = s_L[1 + C_{tur}(q_{sgs}/s_L)^2]^{1/2}$, $C_{tur} = 4/3$;

$s_T \approx 2q_{sgs}/\surd 3$ in the asymptotic regime $s_T \gg s_L$

(Pocheau '94, Peters '99)

Problem: To compute q_{sgs} !

"Forced" turbulent combustion:

3-D "direct" numerical simulations of flames moving in WD matter.

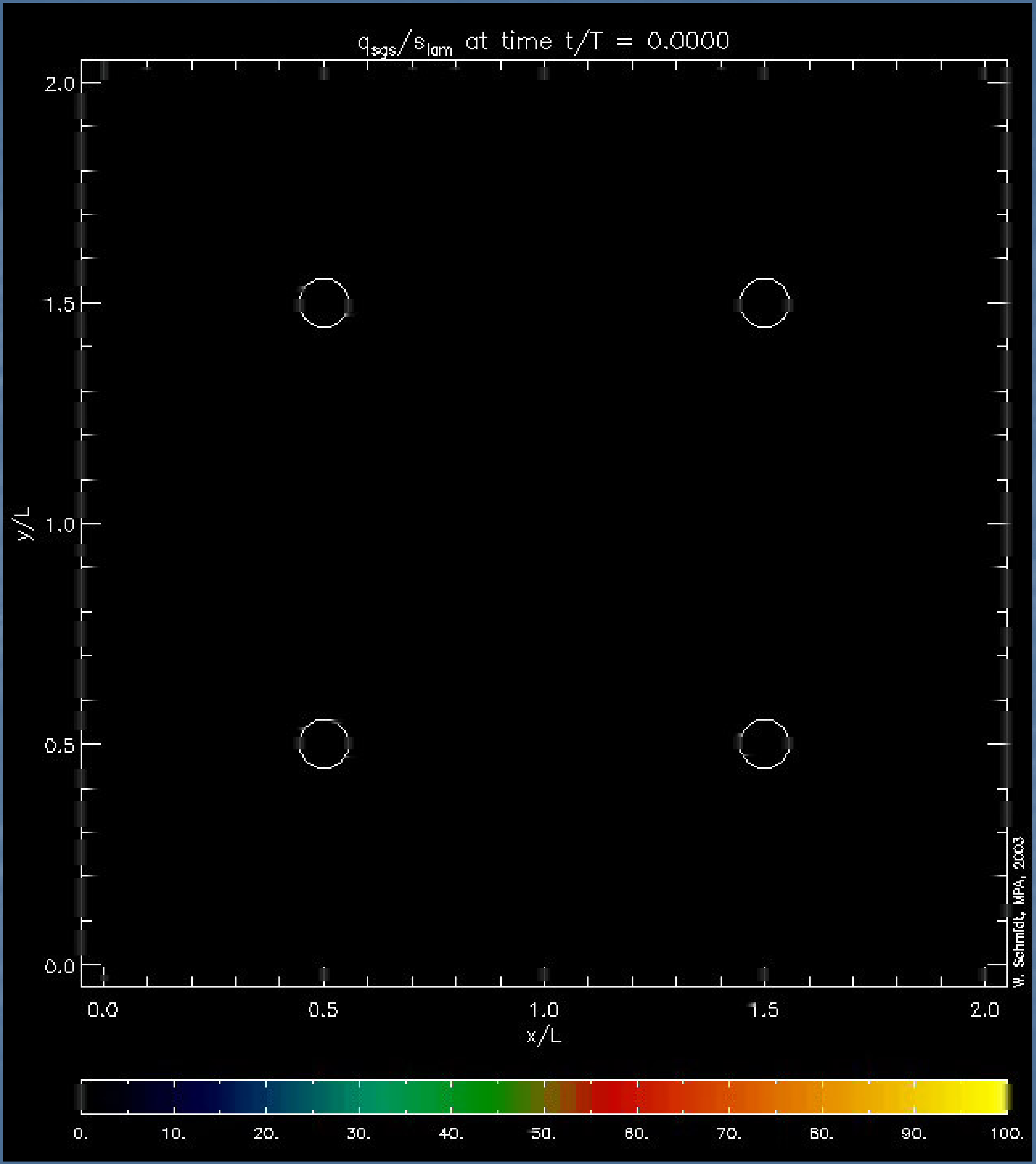
Subgrid-scale velocity

$\rho = 2.9 \cdot 10^9\ gcm^{-3}$

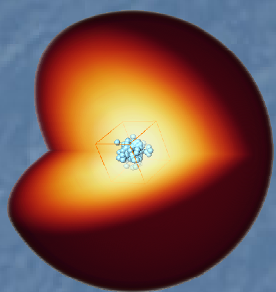
$V_f/s_L = 4$

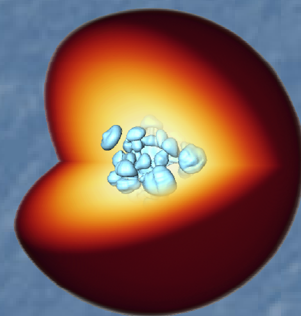
$V_f/c_s = 0.043$

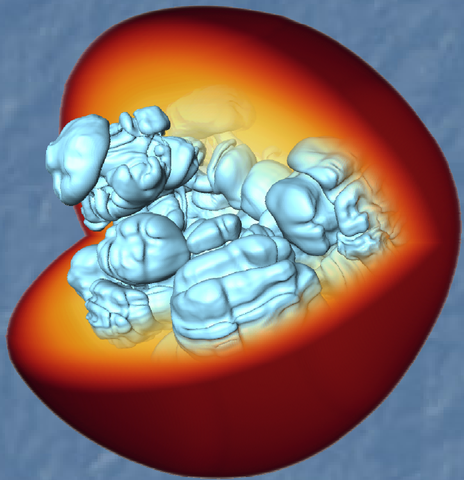
(Schmidt et al., 2005)



2. Full star ("4π") models with an adaptive grid





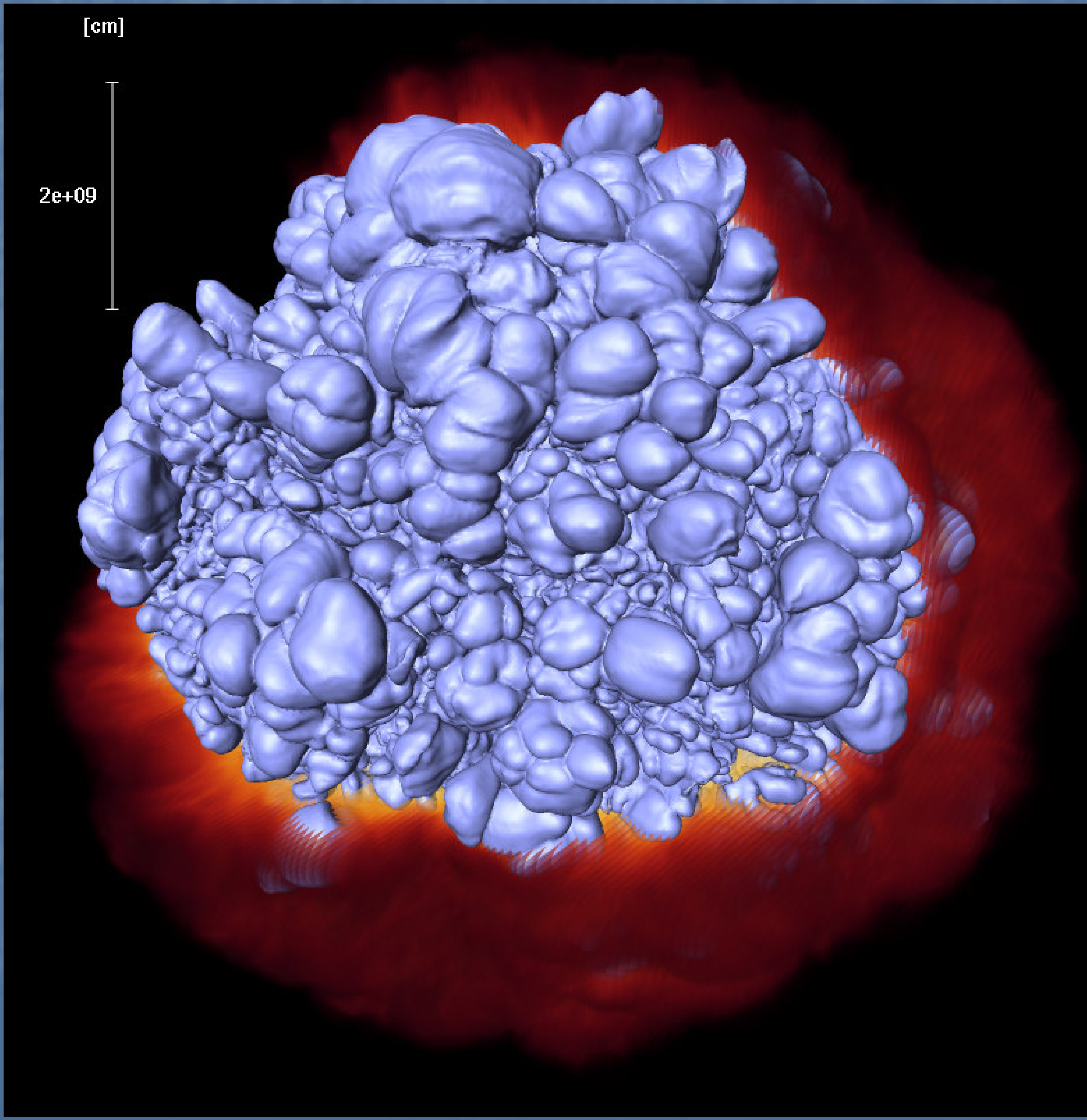


White dwarf!

Röpke & Hillebrandt (2004)

3. A high-resolution model ("the SNOB run")

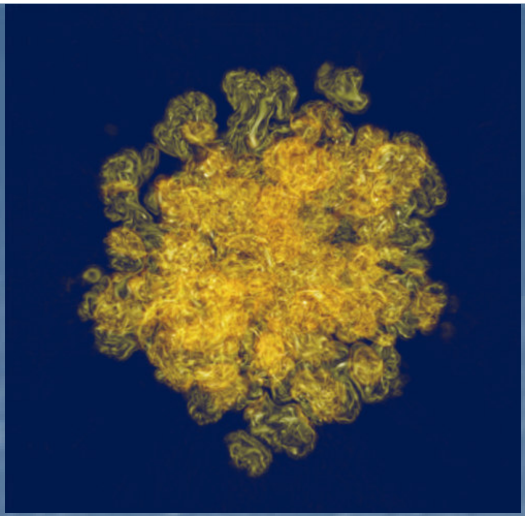
- "4π"
- 1024^3 grid
- initial resolution near the center ≈ 800m
- moving grid
- Local & dynamical sgs-model
- ~ 1,000 h on 512 processors, IBM/Power4, at RZG



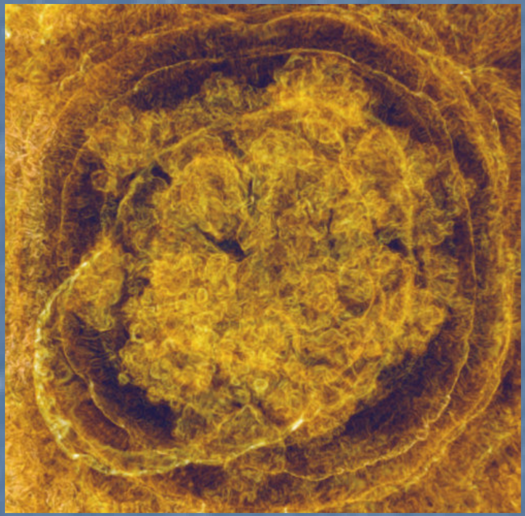
Röpke et al. (2007)


MPI für Astrophysik
Simulation: W. Hillebrandt, F. Röpke
Visualisierung: R. Bruckschen
MAX-PLANCK-GESELLSCHAFT
Time(sec): 0.00 Size(km): 2029.9

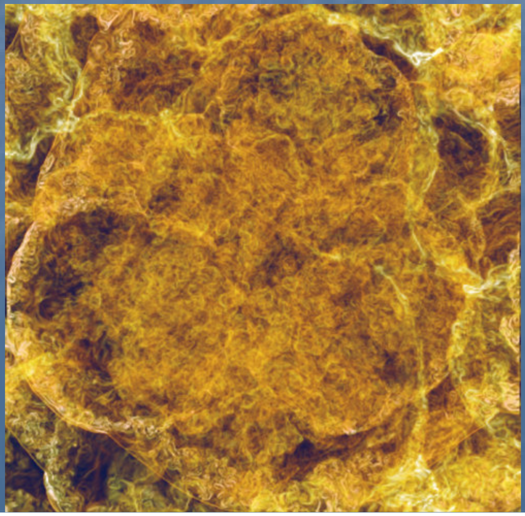
Turbulence?



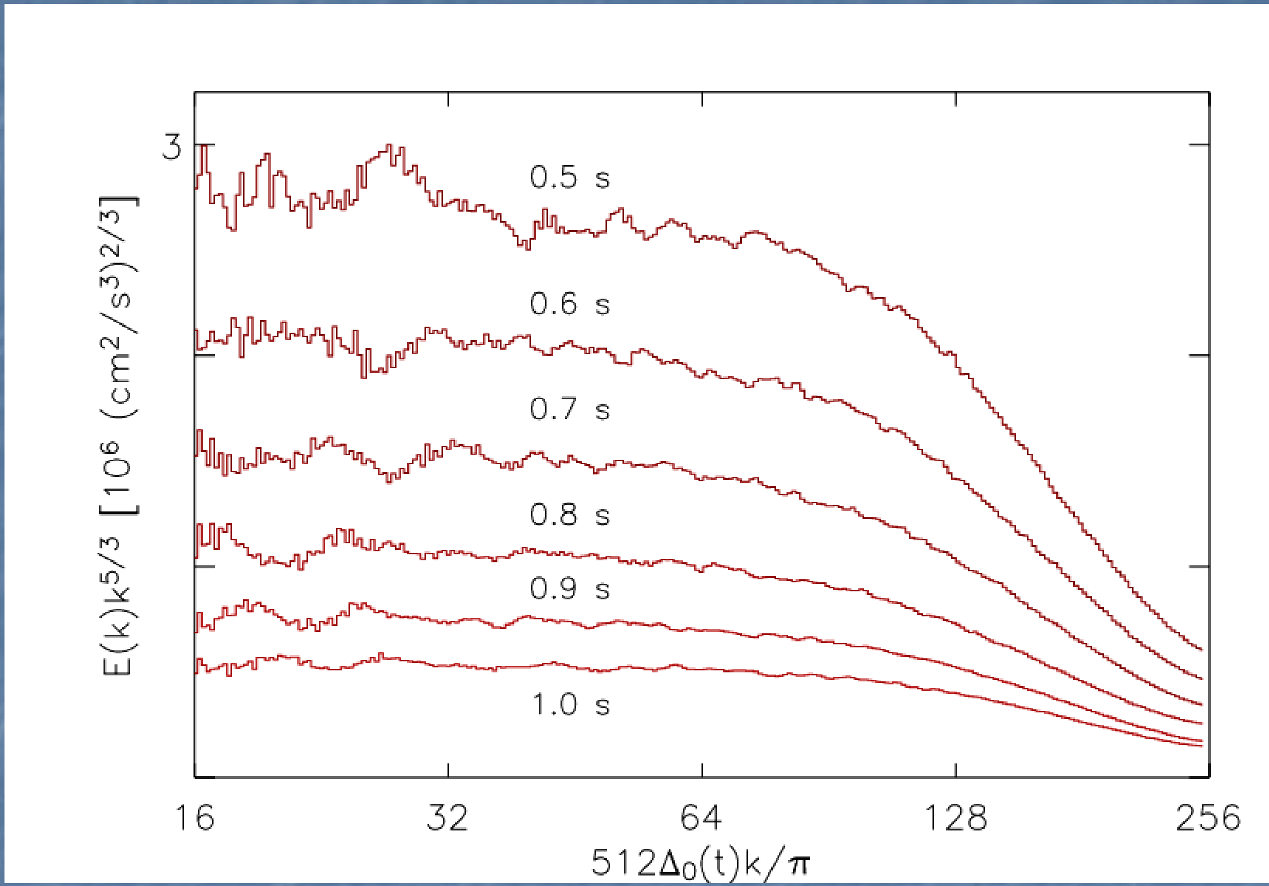
0.25s



0.50s



0.75s



Röpke et al. (2007)

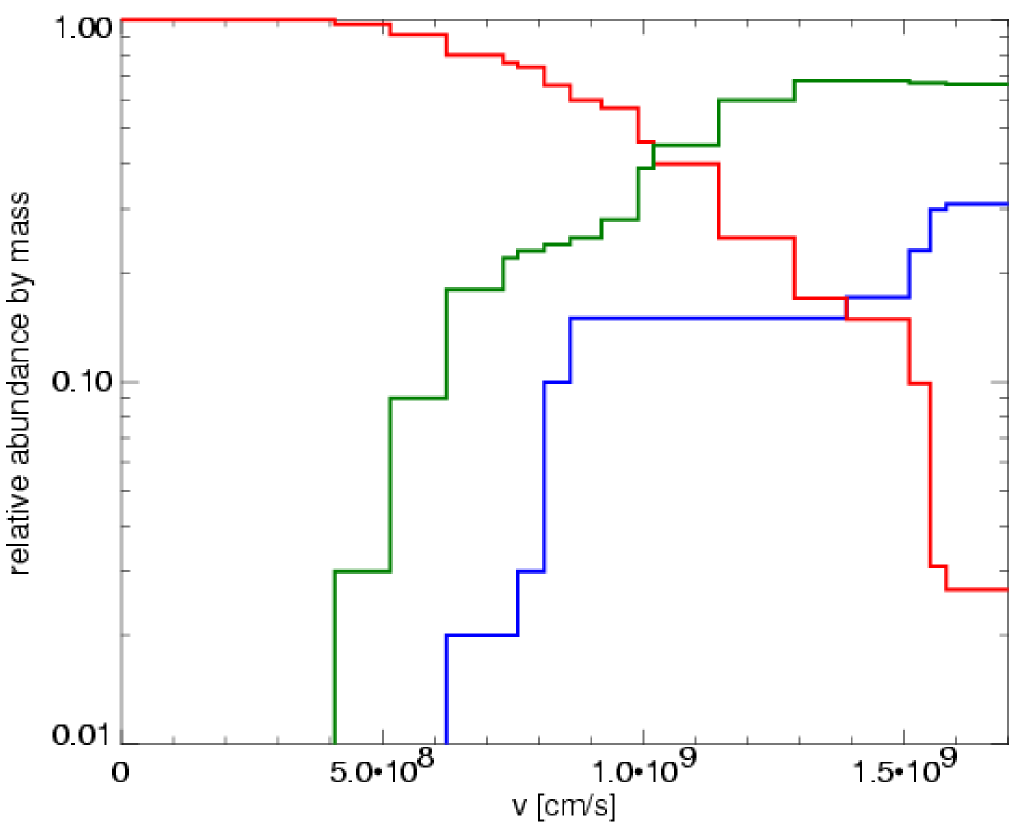
Some important results:

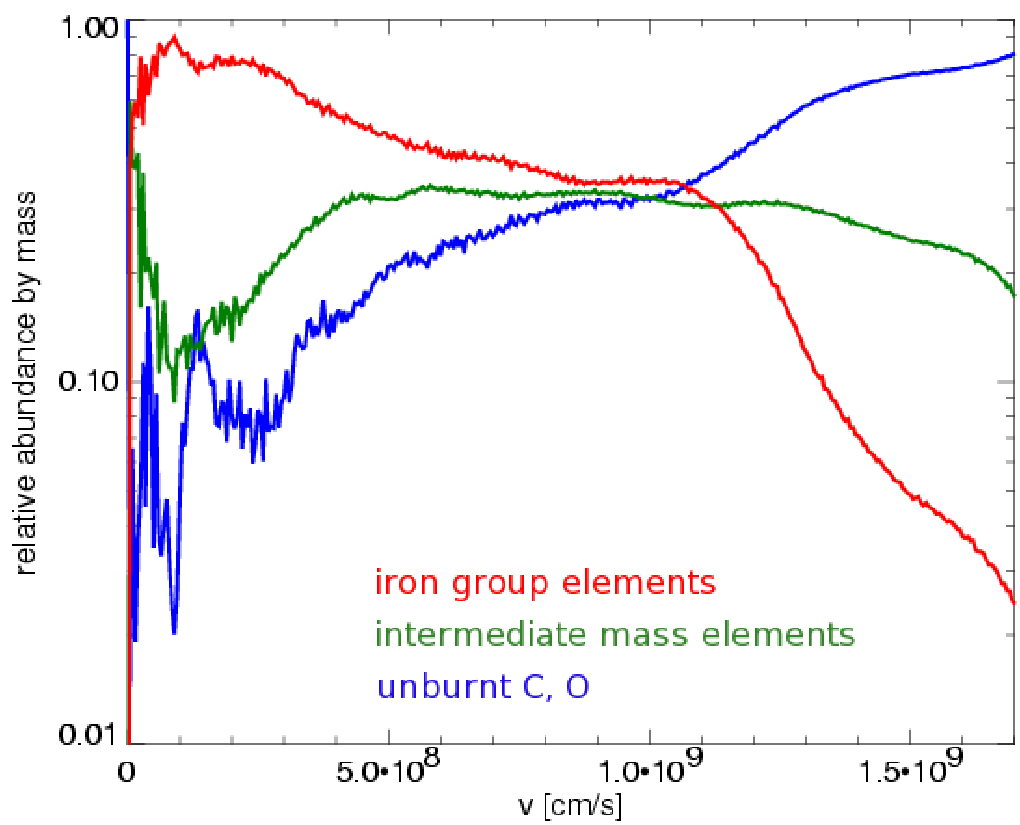
- $E_{kin} = 8.1 \cdot 10^{50}$ erg
- Iron-group nuclei: 0.61 M_{sun} (~ 0.33 M_{sun} ^{56}Ni)
- Intermediate-mass nuclei: 0.43 M_{sun} (from hydro)
- Unburnt C+O: 0.37 M_{sun} (from hydro)
  (less than 0.08 M_{sun} at v<8000km/s)
- Vmax ≈ 17,000 km/s

Good agreement with observations!

Röpke et al. (in preparation)

Example 1:
Element abundances "abundance tomography"



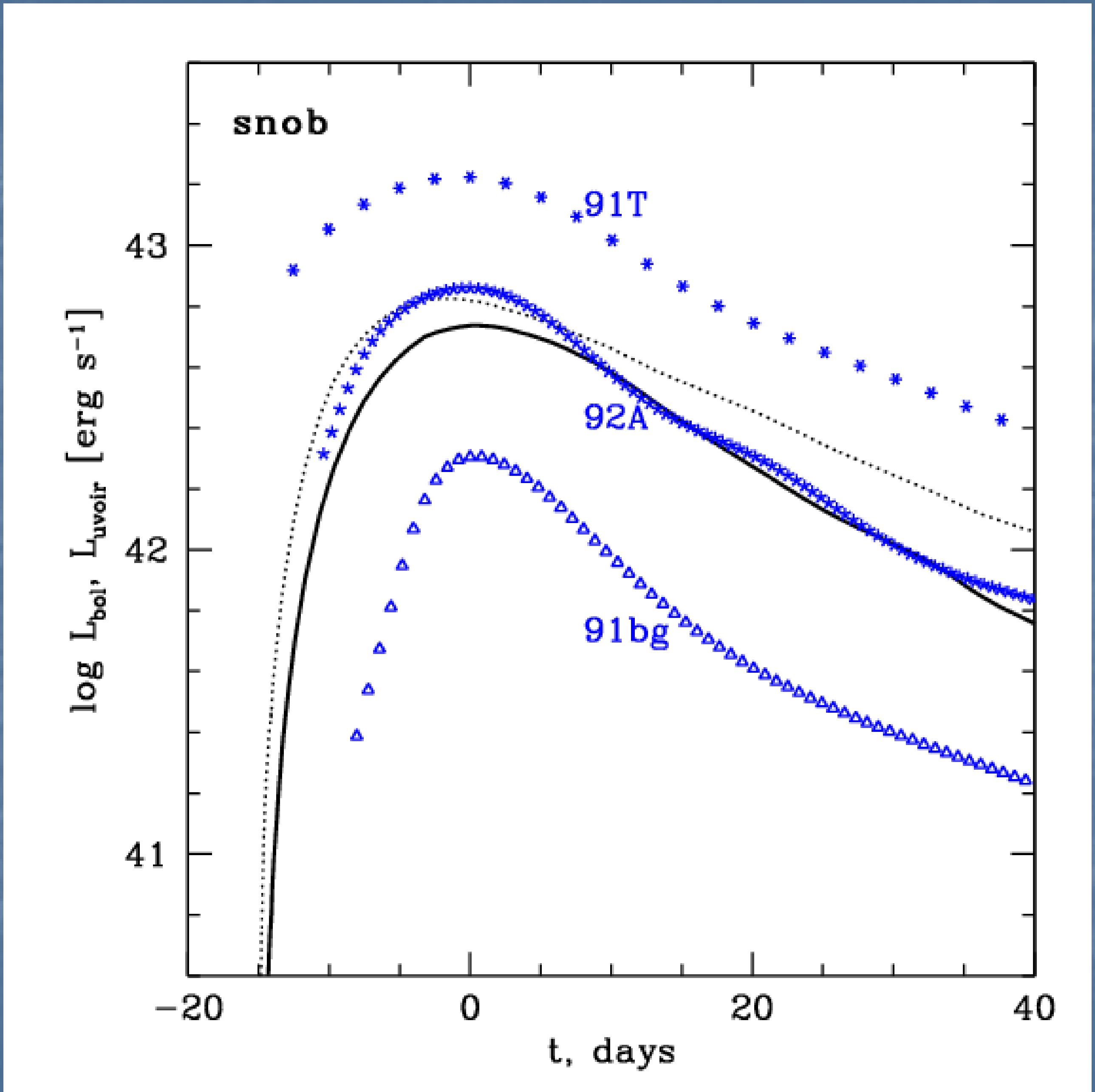


SN 2002bo

SNOB-run

Röpke et al. (2007)

Example 2: Bolometric light curve

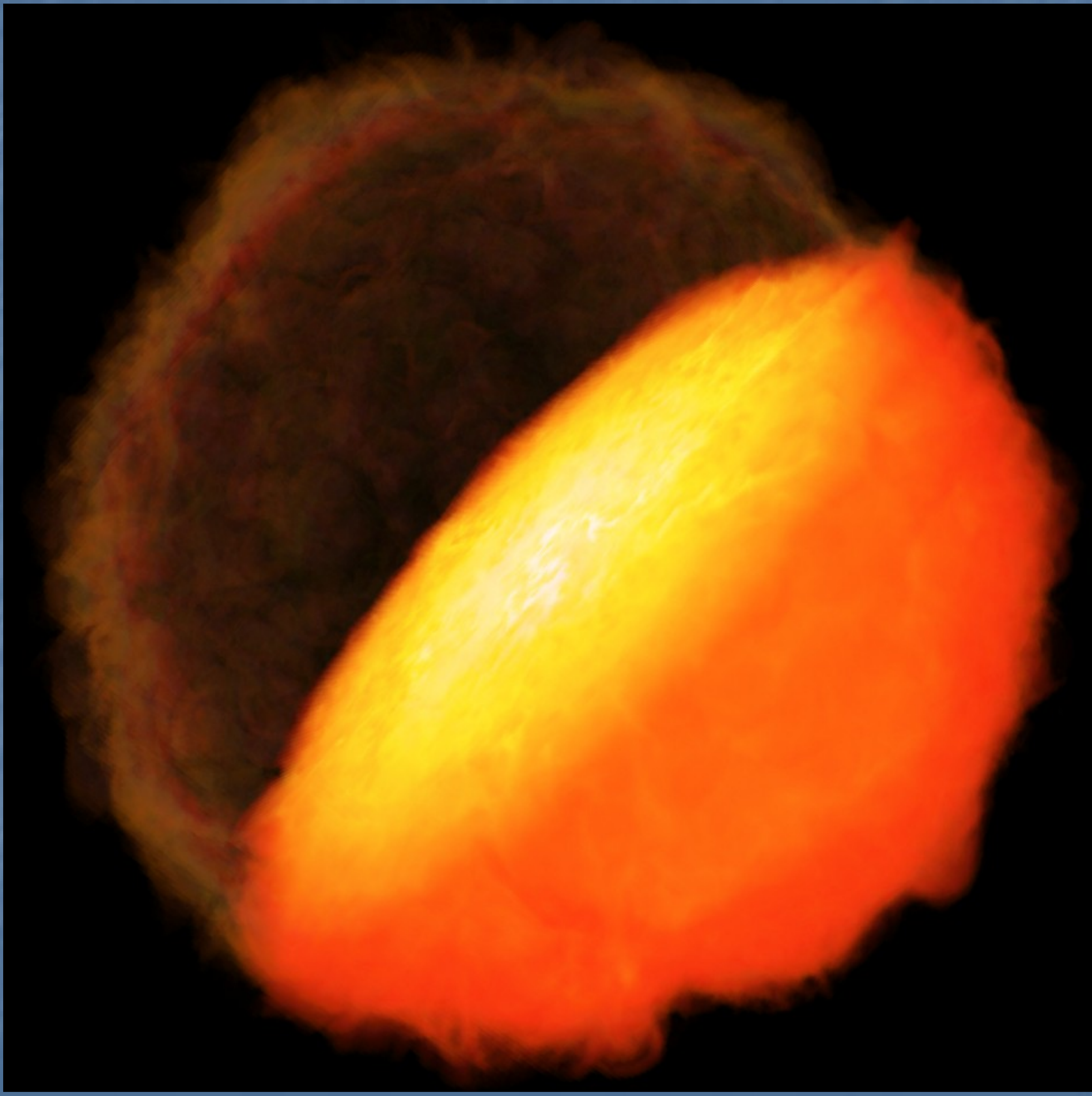


Note:
These are predictions, not fits!

Röpke et al. (2007)

4. Changing physical parameters: Ignition density *(a DEISA project)*

- "4π"
- 640^3 grid
- initial resolution near the center ≈ 1000m
- moving grid
- Local & dynamical sgs-model
- ~ 200,000 CPUh on IBM/Power5, at EPCC



Röpke et al. (in preparation)

Preliminary results:

- $E_{kin} = 7.7 \cdot 10^{50}$ erg
- Iron-group nuclei: 0.55 M_{sun} (mostly ^{56}Ni !)
- Intermediate-mass nuclei: 0.47 M_{sun}
- Unburnt C+O: 0.38 M_{sun}
- Vmax ≈ 16,000 km/s

Lower ignition density makes a supernova less energetic, but brighter!

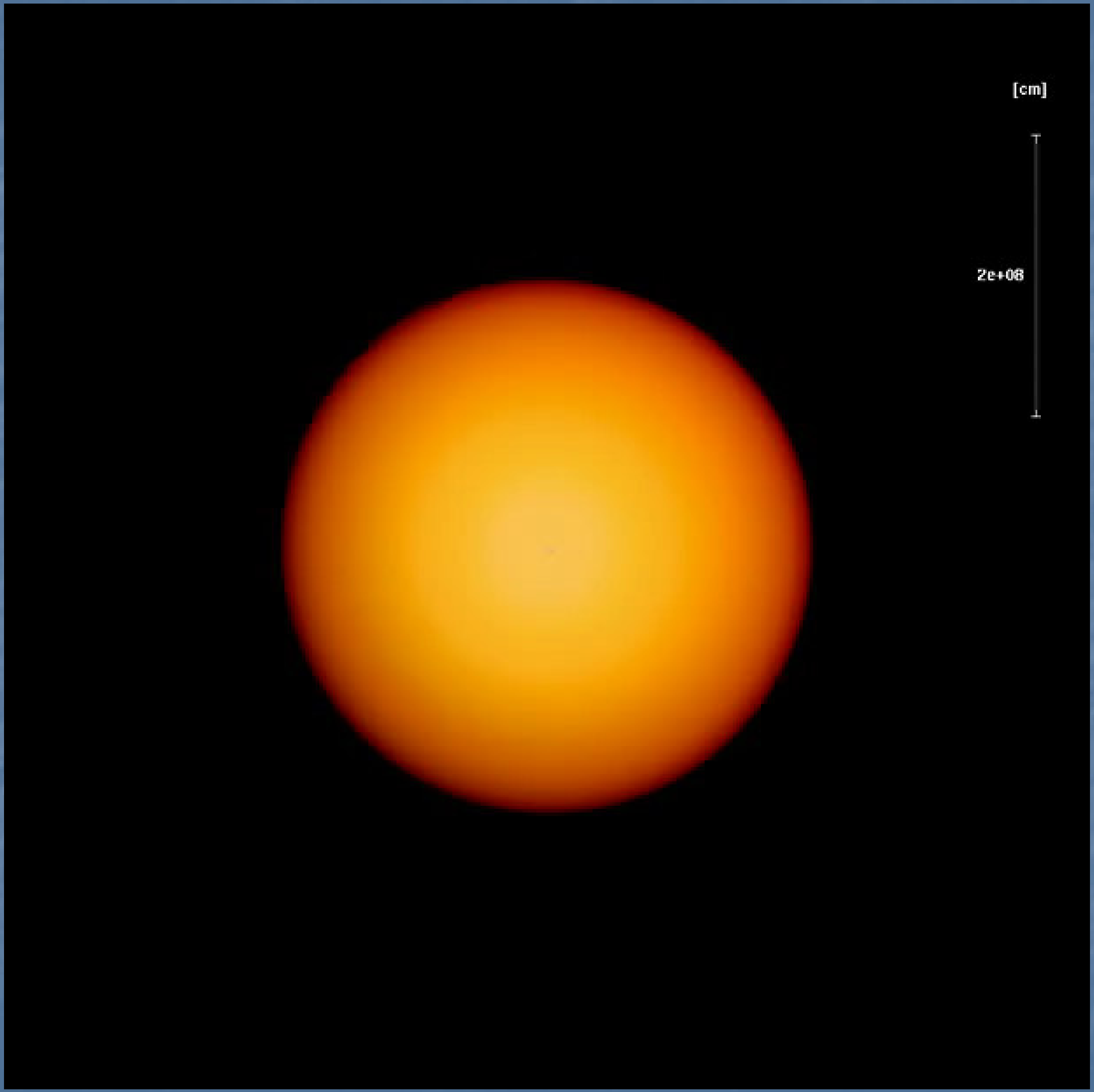
Observations?

Röpke et al. (in preparation)

Summary and conclusions

- "Parameter-free" thermonuclear models of SNe Ia, based on (Chandrasekhar-mass) white dwarfs explode with about the right energy.
- They allow to predict light curves and spectra, depending on physical parameters!
- The diversity may be due to:
  → Ignition conditions (or other physical parameters).

Off-center ignition model: example



Röpke et al. (2006)

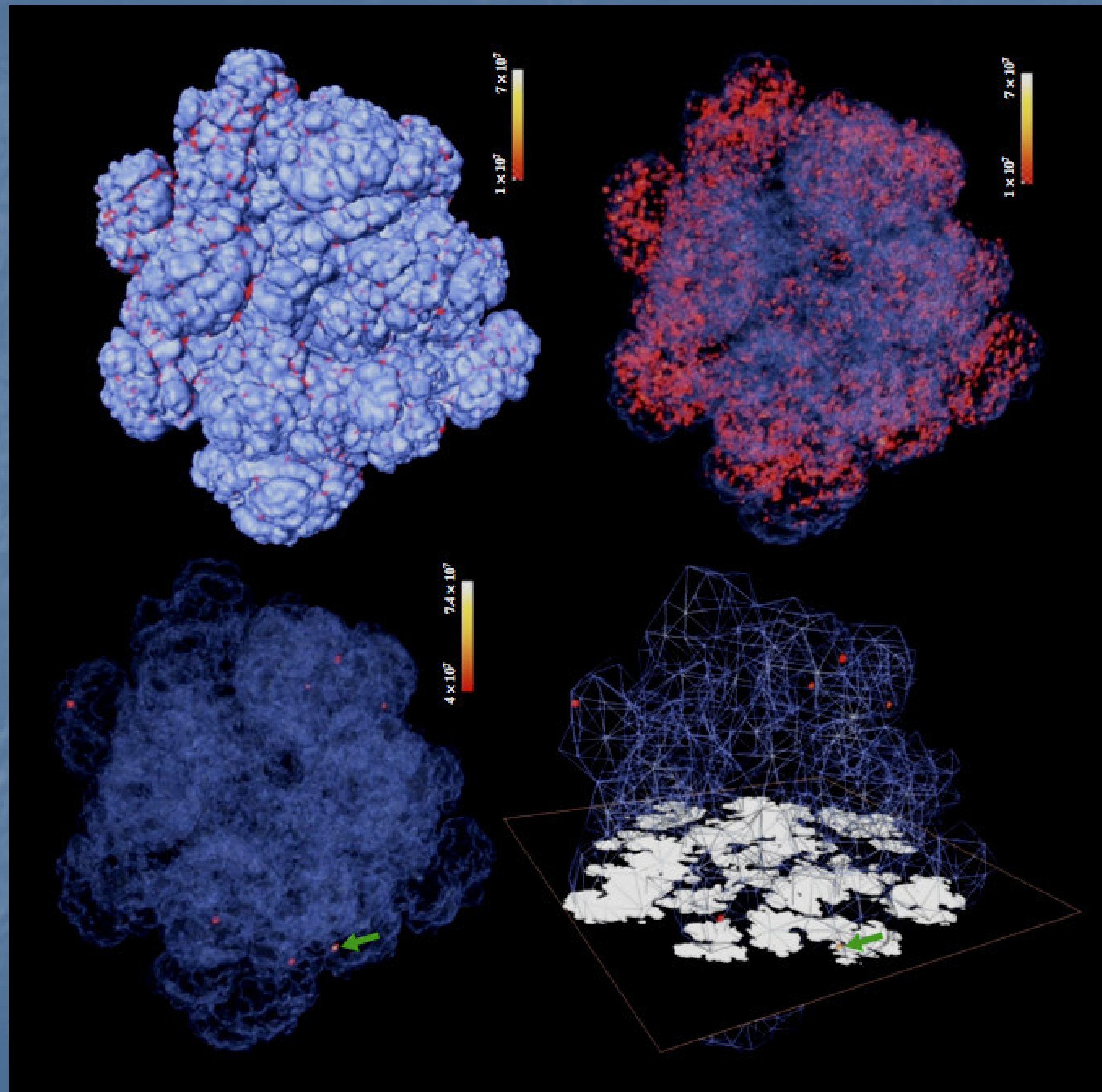
Summary and conclusions

- "Parameter-free" thermonuclear models of SNe Ia, based on (Chandrasekhar-mass) white dwarfs explode with about the right energy.
- They allow to predict light curves and spectra, depending on physical parameters!
- The diversity may be due to:
  → Ignition conditions (or other physical parameters).
  → Or different progenitors ?
  → Or deflagration-detonation transitions?


Size (km) : 5342.16
Time (s) : 0.0120128

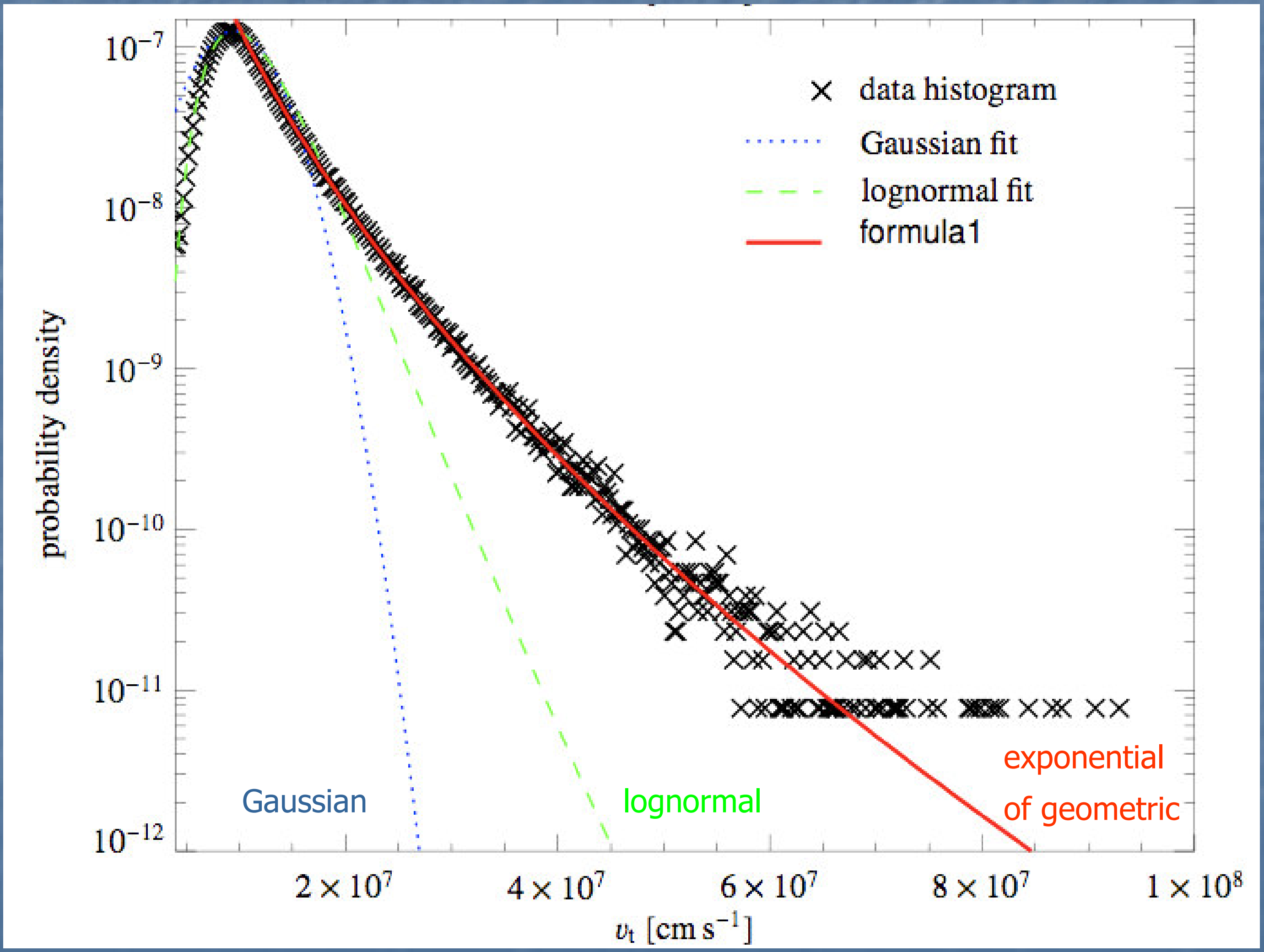
Deflagration-to-Detonation Transitions?

Analysis of turbulent velocity flucutations as predicted by sub-grid scale model at the flame front for densities $1 \ldots 3 \cdot 10^{7}$ g cm^{-3} (Röpke 2007)



Deflagration-to-Detonation Transitions?

High-amplitude turbulent velocity fluctuarions ($\sim 10^8$ cm s^{-1}) occur at the onset of distributed burning regime on sufficiently large area of flame ($\sim 10^{12}$ cm^2)



(Röpke 2007)

More questions and challenges

- Ignition conditions:

  How do WDs reach the critical mass? Center/off-center ignition? One/multiple “points”?

- Combustion modeling:

  Interaction of nuclear flames with turbulence; “distributed burning”; “active turbulent combustion” ? Deflagration/detonation transition: Does it happen? Is it “needed”?

- New generation of ”full-star” models:

  Light curves? Spectra?